Proposed FY13 LRIR:

Shock-Mitigating Multilayered Mechanical Metamaterials (SM^5)

2012 Annual Grantees' Meeting for AFOSR M^4 Program

Arlington, VA

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Integrity ★ Service ★ Excellence

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Fuzes Branch

Munitions Directorate

Air Force Research Laboratory

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Outline

- **Research Team & Acknowledgements**
- **Introduction**
  - Harsh Mechanical Environments: Penetration & Impact
  - State of the Art in Shock Mitigation Schemes
  - Definitions: Metamaterials, band gap materials, etc.
- **Proposed Approach**
  - Overview
  - Analytic framework
  - Optimization
- **Future Work**
- **Summary**
- **Questions**

Research Team, Collaborators, & Up-Front Acknowledgements

Research Team

- **AFRL: Dr. Jason Foley (PI), Dr. Brad Martin (co-PI), Dr. Amanda Schrand, Dr. Jacob Dodson, *et al.***
- **ARA: Dr. Alain Beliveau, Dr. Vincent Luk**

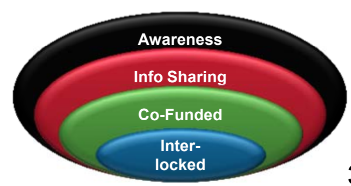
Collaborators

- **ARDEC: Chris Mougeotte, Dr. Jennifer Cordes, Dave Geissler, *et al.***
- **Sandia National Labs: Dr. Scott McEntire *et al.***
- **Univ. of Texas-San Antonio: Prof. John Foster**
- **Univ. of South Carolina: Prof. Jinkyu "JK" Yang**
- **CalTech: Prof. Chiara Daraio**

and many others…

Support

- **Air Force Office of Scientific Research**
  - Dr. Byung-Lip "Les" Lee and Dr. David Stargel
- **DoD SMART Scholarship for Service Program**



DoD Harsh Environments

Stress/Pressure

Vacuum — Impact Stress — Detonation Pressure

~0 Pa — >50 MPa — >1 GPa

Shock/Vibration

Weapon Thermomechanical Environment

Flight Operations — Rocket Launch — Hard Target Penetration — Explosively-Driven Shock

100 m/s² — ~1 km/s² — >10⁶ m/s² — >10⁸ m/s²

Temperature

Cryogenics — Solid Oxide Fuel Cells — Shock Heating — Nuclear Sources

77 K — ← Mil Std → — ~1200 K — >2000 K — >2500 K

Erosion/Corrosion/Wear

Humidity — Saltwater Corrosion — Penetration Erosion — Blast Ablation

← Eglin AFB → — >10 mm — >1 mm/us

Power and Fields

Persistent Power Sources — RF and High Speed Electronics — Capacitive Discharge

>10^3 W·h/kg — >100 GHz·100mA = 10^7 A/s — >10^9 A/s

Radiation

Geologic Background — Space Environment — Nuclear Reactor

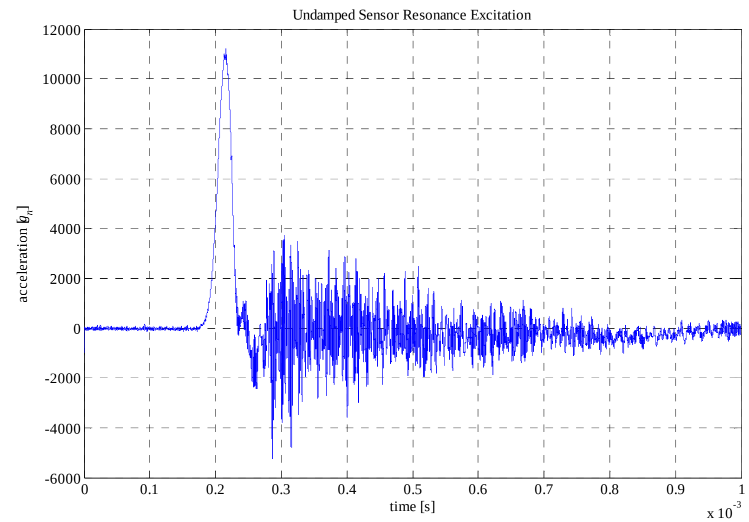
~360 mrem/yr — ~10^{10} cm^{-2} — 10^{14} cm^{-2} s^{-1}

Weapon Dynamic Environment

Sled Test Video (Dist A, 96ABW-2010-0139).wmv

Weapon Dynamic Environment

- **Impact and shock is relevant to many fields**
  - Crash testing
  - Defense
  - Blast protection
  - Oil & Mining
- **Common features**
  - Impulse stress waves
    - Short rise time
    - High frequency waveforms
    - High amplitude
    - Multiaxial
  - Wide range of damage
    - Sensor resonance
    - Material failure
    - Fatigue, etc.



Sensor resonance from impact loads

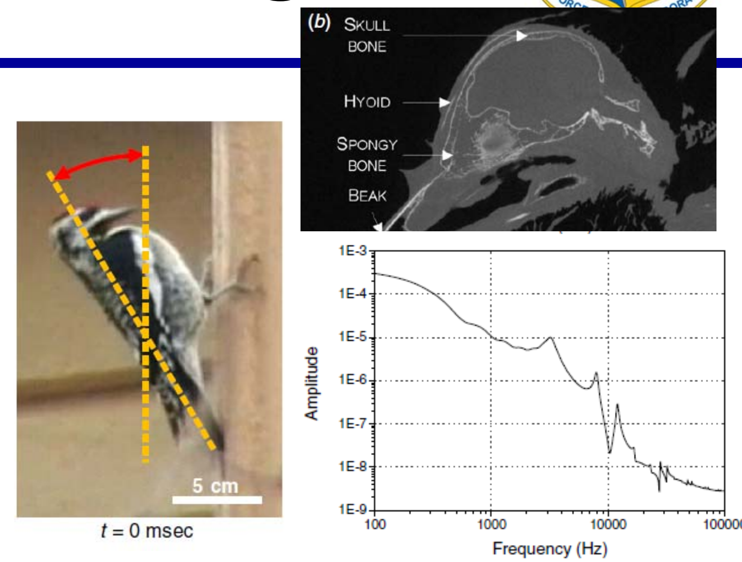
Fractures Group, Cavendish Laboratory, Cambridge

Blast-Induced High-Rate Material Fracture

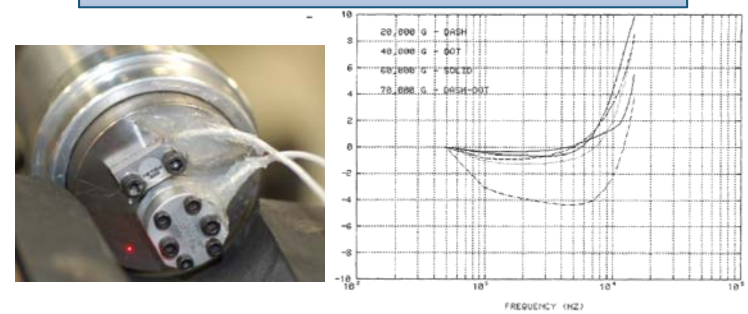
State of the Art in Shock Mitigation

<u>Classes</u> ***(by dissipation mechanism)***

- **Mechanical deformation**
  - Automotive “crumple zones”
- **Constrained layer damping**
  - Woodpecker skull (biomimetic) [11]
- **Energy localization**
  - Functional polyurea nanoparticles [12]
- **Viscoelastic/viscoplastic**
  - Polysulfide-isolated mount [13]
- **Superelastic**
  - NiTi shape memory alloy [14]
- **Multilayered mechanical filter**
  - Metal & polymer “bandstop” filter [15]



Woodpecker brain isolation [11]



Polysulfide filter [13]

[11] Yoon, S.-H., and Park, S., 2011, "A mechanical analysis of woodpecker drumming and its application to shock-absorbing systems," Bioinspiration & Biomimetics, 6(1), p. 016003.

[12] Holzworth, K., Williams, G., and Nemat-Nasser, S., 2012, "Hybrid Polymer Grafted Nanoparticle Composites for Blast-induced Shock-wave Mitigation," Proc. SEM International Conference & Exposition on Experimental and Applied Mechanics, Costa Mesa, CA.

[13] Bateman, V. I., Brown, F. A., and Nusser, M. A., 2000, "High Shock, High Frequency Characteristics of a Mechanical Isolator for a Piezoresistive Accelerometer, the ENDEVCO 7270AM6," Report SAND2000-1528 Sandia National Laboratory

[14] S. Nemat-Nasser and W.-G. Guo, 2006, “Superelastic and cyclic response of NiTi SMA at various strain rates and temperatures”, *Mech Materials* 38, pp 463-474.

[15] N.A. Winfree et al, 2010, “Mechanical filter for sensors”, US Patent 7706213

Proposed Research Objectives

Technical Challenge

- **Improve survivability of complex systems in high shock environments (e.g., ballistic impact & explosive loading)**

Technical Objective

- **Identify and demonstrate concepts for broadband shock mitigation**
  - Attenuate impulsive uniaxial and multiaxial stress waves with simultaneous high amplitude stress and high frequency content

Proposed Approach: Multilayered Mechanical Metamaterials

- **Develop theory/models in metamaterials framework**
  - "Bottom-up", e.g., uniaxial elastic is initial focus
  - End state: Broadband spectral framework with rate-/temp-dependent materials
- **Identify best candidates using optimization**
  - Multiobjective, constrained
  - Also includes consideration of uncertainty
- **Demonstrate using state-of-the-art experiments**
  - Validate models and performance in shock-like loading regimes

Metamaterials & Other Buzzwords

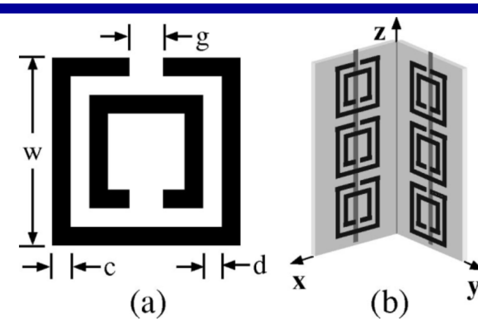
- ***Metamaterials* [1]**
  - Definition: Engineered materials designed w/properties not occurring naturally
  - "Effective" macroscopic properties strongly dependent on (nano-/micro-) structure & material ("unobtainium")
- ***Phononic Crystals (PC)/Band Gap (PBG) Materials***
  - Definition: Artificial periodic (crystalline) composites where structure influences wave propagation [2]
  - Interactions: Bragg (lattice) + Mie (geometric) scattering
    - **Generally constant "single scatterer" assumption**
- ***Acoustic Band Gap (ABG) Materials***
  - Definition: Composite materials with defined band baps in or near the acoustic range (~20 Hz to 20 kHz)
  - Interactions: Elastic wave propagation + Bloch periodicity (pressure)
- ***Superlattices (SL)***
  - Definition: Multilayered periodic heterostructures (i.e., a microstructure with different materials) made of thin crystalline films,
    - **Individual film thicknesses ranging from less than 1 nm to over 100 nm**
    - **Period: Characteristic pattern of crystalline films (e.g., a pair of different films called a "bilayer") that is repeated many times**
  - Interactions: Phonon (elastic) propagation on lattice (band-folding, scattering)

[1] Shelby, R. A., Smith D.R., Shultz S., and Nemat-Nasser S.C., 2001, "Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial", *Applied Physics Letters* 78 (4), pp. 489-491.

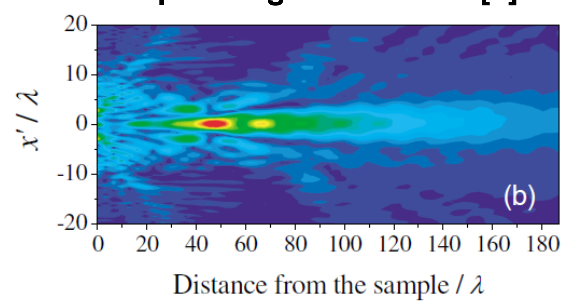
[2] Lu, M.-H., Feng, L., and Chen, Y.-F., 2009, "Phononic crystals and acoustic metamaterials," Materials Today, 12(12), pp. 34-42.

[3] Yang, S., Page, J. H., Liu, Z., Cowan, M. L., Chan, C. T., and Sheng, P., 2004, "Focusing of Sound in a 3D Phononic Crystal," Physical Review Letters, 93(2), 024301.

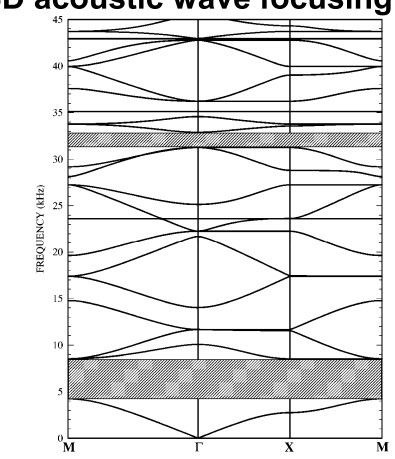
[4] Vasseur, J. O., Deymier, P. A., Khelif, A., Lambin, P., Djafari-Rouhani, B., Akjouj, A., Dobrzynski, L., Fettouhi, N., and Zemmouri, J., 2002, "Phononic crystal with low filling fraction and absolute acoustic band gap in the audible frequency range: A theoretical and experimental study," Physical Review E, 65(5), p. 056608.



Split Ring Resonators [1]



3D acoustic wave focusing [3]



Acoustic band structure [4]

Sample of Metamaterials Work

First Author	Year	Materials/ Geometry	*N*-D	Feature Size *r* or *l* [m]	Lattice Spacing *a* [m]	Freq Range/ Bandwidth $\Delta\omega$ [Hz]	Notes/Comments	Ref.
Liu	2000	Cubic array of Pb/silicone spheres	3D	~5 mm	30 mm	250 to 2k		[5]
Vasseur	2002	Square planar array of filled/hollow Cu tubes in air	2D	14 mm	30 mm	0 to 50k		[4]
Tanaka	1999	Square lattice of AlAs cylinders in GaAs matrix	2D	*A* (arbitrary)	*a* (arbitrary)	~ *a/v* (normalized)	Surface acoustic wave (SAW) theory	[6]
Pennec	2004	Square planar array of steel tubes w/air, Hg in air	2D	0.9-1.4 mm	5 mm	0 to 300k	ABG w/ tunability and multiplexing	[7]
Tang	2004	Thin film sandwiches w/ electrorheological material	1D	0.1 mm	0.1 mm	80 to 200	Simple transmission experiments	[8]
Dhar	1999	Lithographically patterned Al film on glass substrate	1D	~1 μm	3-3.75 μm	100-800 MHz	Measured w/ ps transient grating	[9]
Yang	2004	FCC cubic array of WC beads in water	3D	0.4 mm	0.8 mm	0.98-1.2 MHz	3-D focusing of waves	[1]
Lu	2009	(Review article)					Review article (PC and AMM)	[2]

[5] Liu et al., 2000, "Locally Resonant Sonic Materials," *Science* 289 (5485), pp 1734-1736.
[6] Tanaka, Y., and Tamura, S.-I., 1999, "Two-dimensional phononic crystals: surface acoustic waves," *Physica B: Condensed Matter* 263-264, pp. 77-80.
[7] Pennec, Y., Djafari-Rouhani, B., Vasseur, J. O., Khelif, A., and Deymier, P. A., 2004, "Tunable filtering and demultiplexing in phononic crystals with hollow cylinders," Physical Review E, 69(4), p. 046608.
[8] Hong, T., Chunrong, L., and Xiaopeng, Z., 2004, "Tunable characteristics of a flexible thin electrorheological layer for low frequency acoustic waves," Journal of Physics D: Applied Physics, 37(16), p. 2331.
[9] Dhar, L., and Rogers, J. A., 2000, "High frequency one-dimensional phononic crystal characterized with a picosecond transient grating photoacoustic technique," Applied Physics Letters, 77(9), pp. 1402-1404.

Our Approach

- **Simultaneously consider the depth and breadth of the shock mitigation problem…**

Theoretical Mechanics	**Materials Modeling**	**Optimization**
• Dispersion • Wave modes/polarization • Metamaterials	• Rate-dependent • Temperature-dependent • Complex properties	• Topological Optimization • Multi-objective

Experimental Mechanics	**Fabrication**	**Analysis**
• Shock/vibration analysis: transmissibility, damping • High rate test methods	• Reproducibility • Characterization • Distribution of properties	• Uncertainty quantification • Stochastic analysis • Spectral element models

…beginning with simple 1-D geometries (multilayered films) and well-known materials (metals, polymers) in a metamaterials framework

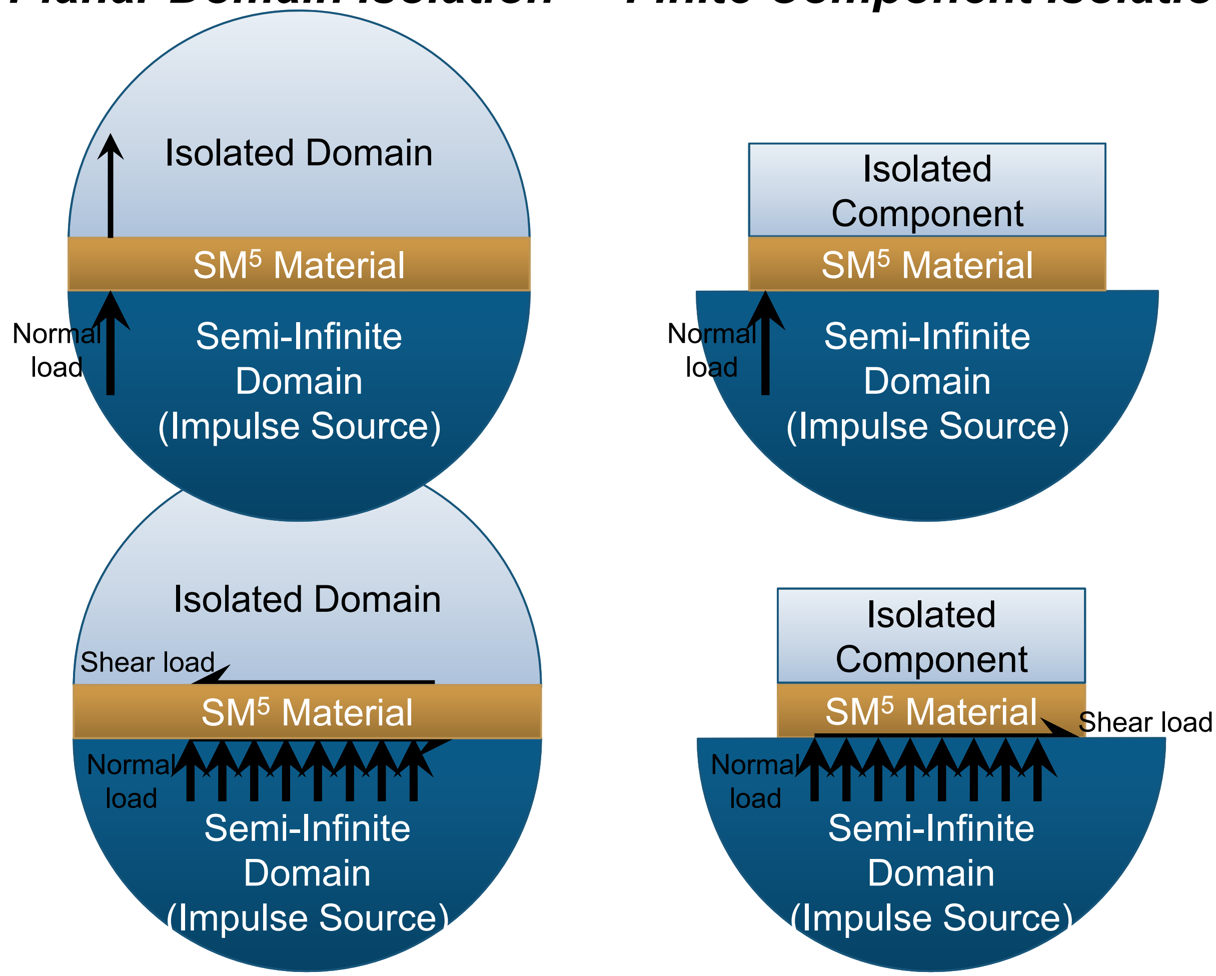
Geometry

Driven by system/subsystem isolation goal

Planar Domain Isolation ***Finite Component Isolation***

Uniaxial wave propagation

Biaxial wave propagation



Materials

Material classes

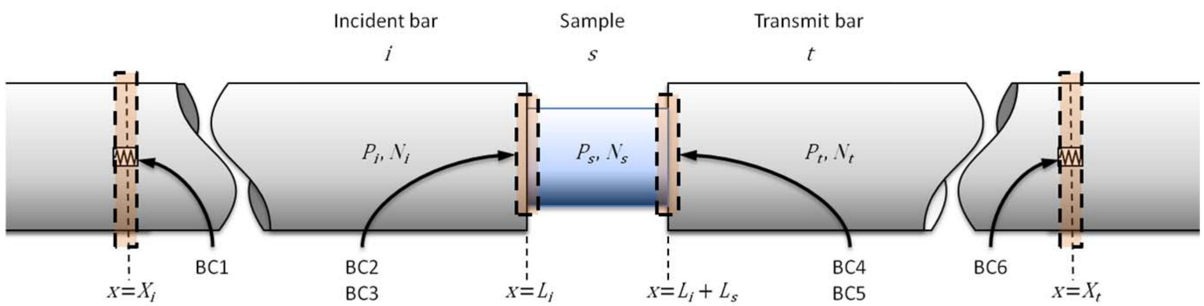
- **Metals**
  - W, Ti, steel, Cu
- **Polymers**
  - Epoxy, polysulfide, PMMA, PTFE
- **Composites**
  - G10, syntactic foam, Ultem

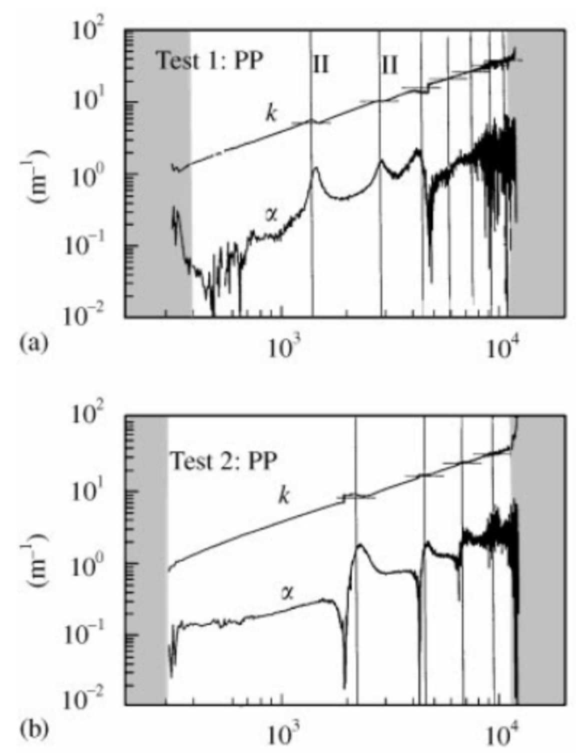
Constitutive behavior

- **“Effective” properties**
  - Anisotropic response from isotropic films
  - Strongly dependent on interfaces and spacing
- **Time-Temperature Equivalency**
  - Applicable to polymers
- **Spectral properties**
  - Complex moduli as a function of frequency…

Material Spectral Constitutive Response (Frequency Domain)

- **Materials can be modeled with frequency dependent (complex) properties**
  - Complex modulus $\tilde{E}(\omega) = E^{'}(\omega) + iE^{''}(\omega)$
  - γ: Re→attenuation (α), Im→ propagation (κ)
- **Developed solution for 1-D and 2.5-D wave transport with complex media**
  - Working on application to SHPB data sets





$$\tilde{\varepsilon}_j(x,\omega) = \tilde{P}_j(\omega)e^{-\gamma_j x} + \tilde{N}_j(\omega)e^{\gamma_j x}$$

$$\gamma = i\omega\sqrt{\frac{\rho}{\tilde{E}}}$$

Hillström, L., Mossberg, M., and Lundberg, B., 2000, "IDENTIFICATION OF COMPLEX MODULUS FROM MEASURED STRAINS ON AN AXIALLY IMPACTED BAR USING LEAST SQUARES," Journal of Sound and Vibration, 230(3), pp. 689-707.

Wave Properties in Various Media

$Z = F/v = \rho A c$ | $c = \sqrt{E/\rho} = f\lambda$

	Material	Elastic Modulus E [GPa]	Density ρ [kg/m^3]	1-D Impedance $Z'' = Z/A$ [x 10^6 kg/m^{2}s]	1-D Wave Speed c [m/s]
Metals	6/4 Titanium	104	4420	21.4	4840
	Maraging Steel	188	8080	39.1	4835
	Tungsten	329	16920	75.3	4406
	Copper	115	8960	32.1	3583
Polymers	Polycarbonate	2.3	1200	1.86	1550
	Epoxy	2.3	1140	1.62	1420
	PVC	1.6	1380	1.48	1077
Composites	PBX(1)	~0.5 (0.1-2.9+)	~1800	1.89	527
	G10(2)	~18.8 (*x*) ~7.8 (*z*)	~1700	5.64 (*x*) 3.64 (*z*)	3320 (*x*) 2140 (*z*)
	CFRP	~1.5	~1500	1.50	1000

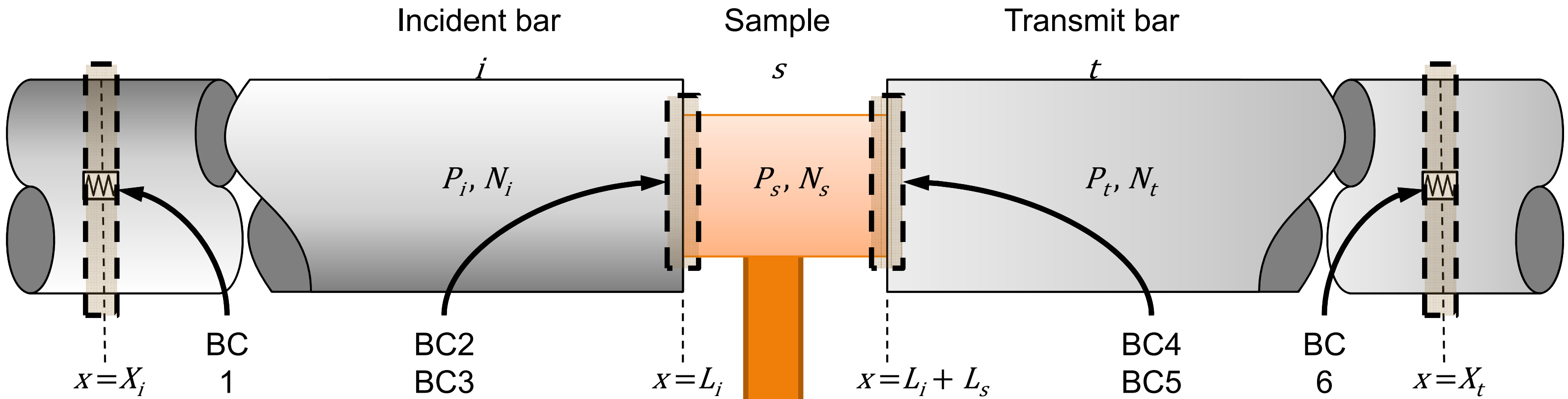
Frequency f [Hz]	Wavelength λ [m]
1	4800
100	48
10k	0.48
1M	4.8m
100M	48μ

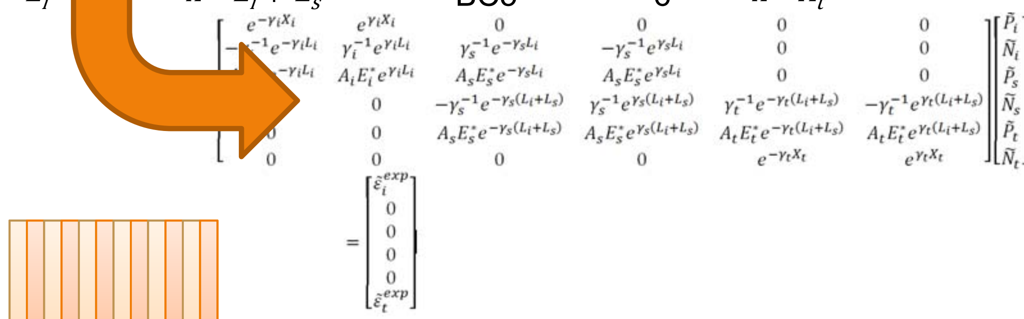
Frequency f [Hz]	Wavelength λ [m]
1	1077
100	1.1
10k	0.11
1M	1.1m
100M	11μ

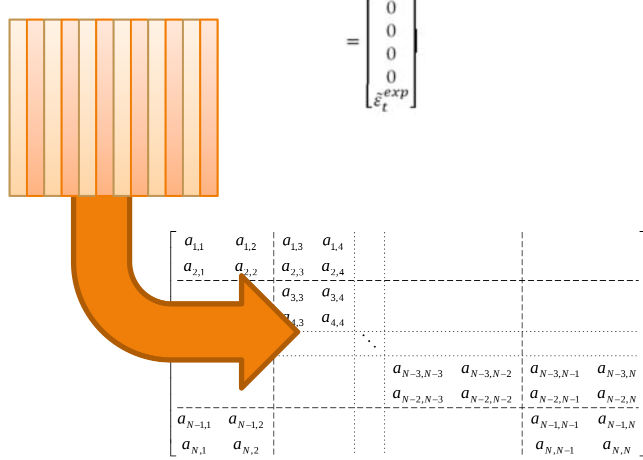
(1) Generalized from several open literature values for PBX-9501 properties

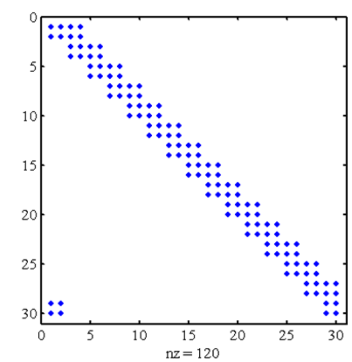
(2) K. Ravi-Chandar and S. Satapathy, 2006, “Mechanical Properties of G-10 Glass–Epoxy Composite”, Institute for Advanced Technology, The University of Texas at Austin, IAT.R 0466

Analysis Solution







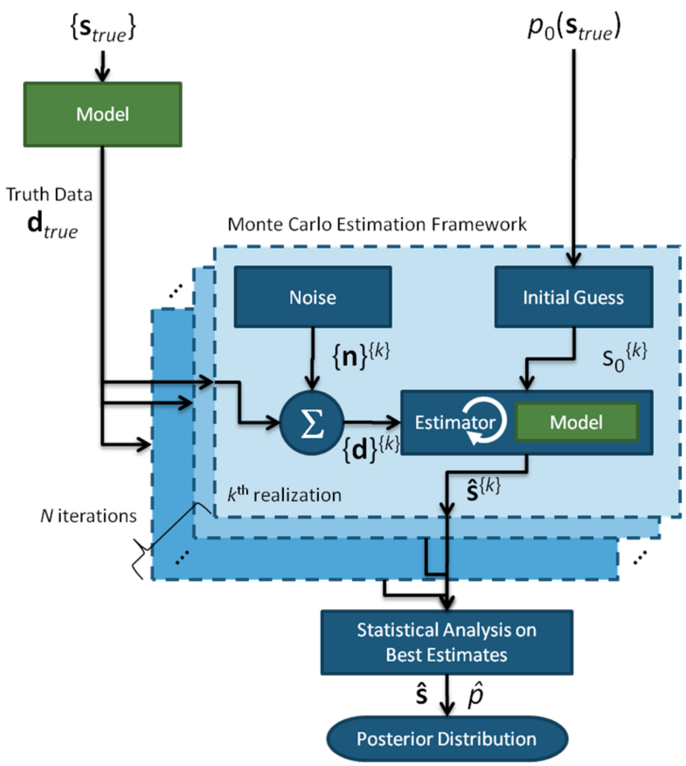


Initial case:

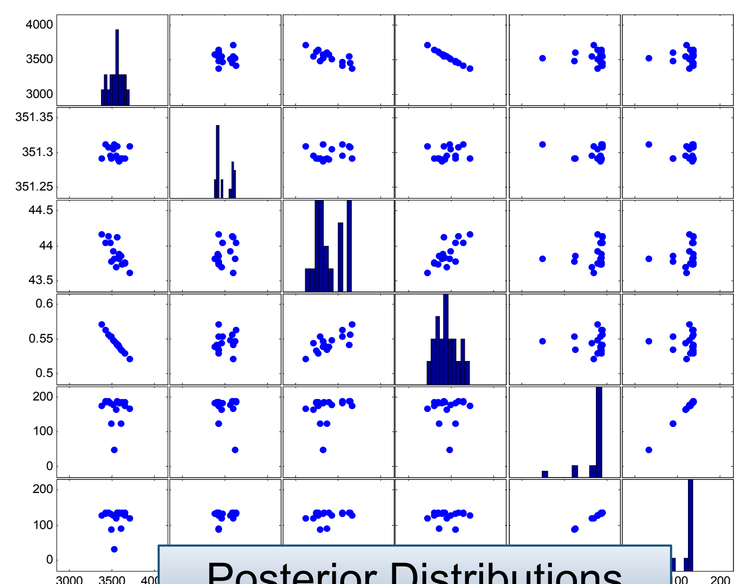
- **Simple 1-D geometry**
  - Limit: Kolsky bar behavior
- **Simultaneous coupled problem for wave terms**
  - Arbitrary *N*-layer solution
  - Banded coupling equation

Optimization

- **Topological Optimization**
  - Initial optimization criteria: Spectral transmissibility

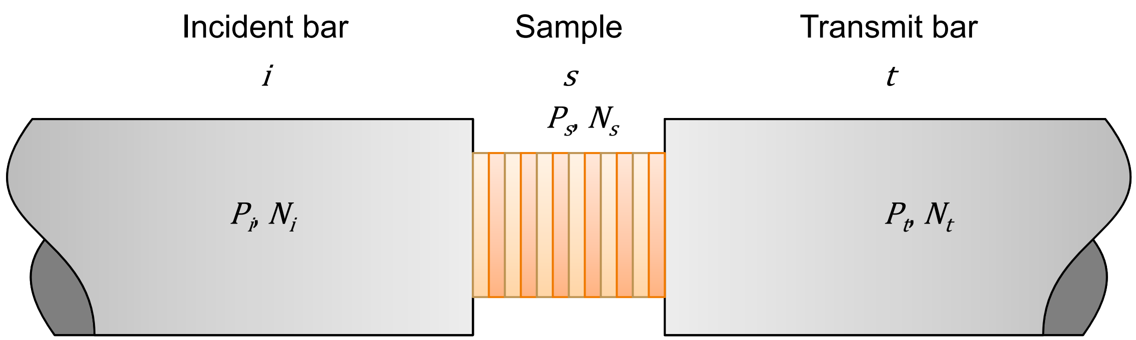


- **Uncertainty Quantification**
  - Bayesian framework for estimating parameters
  - Prior information, observation and process uncertainty
  - Monte Carlo truth modeling



Posterior Distributions

Initial Shock Filter Design Optimization Problem

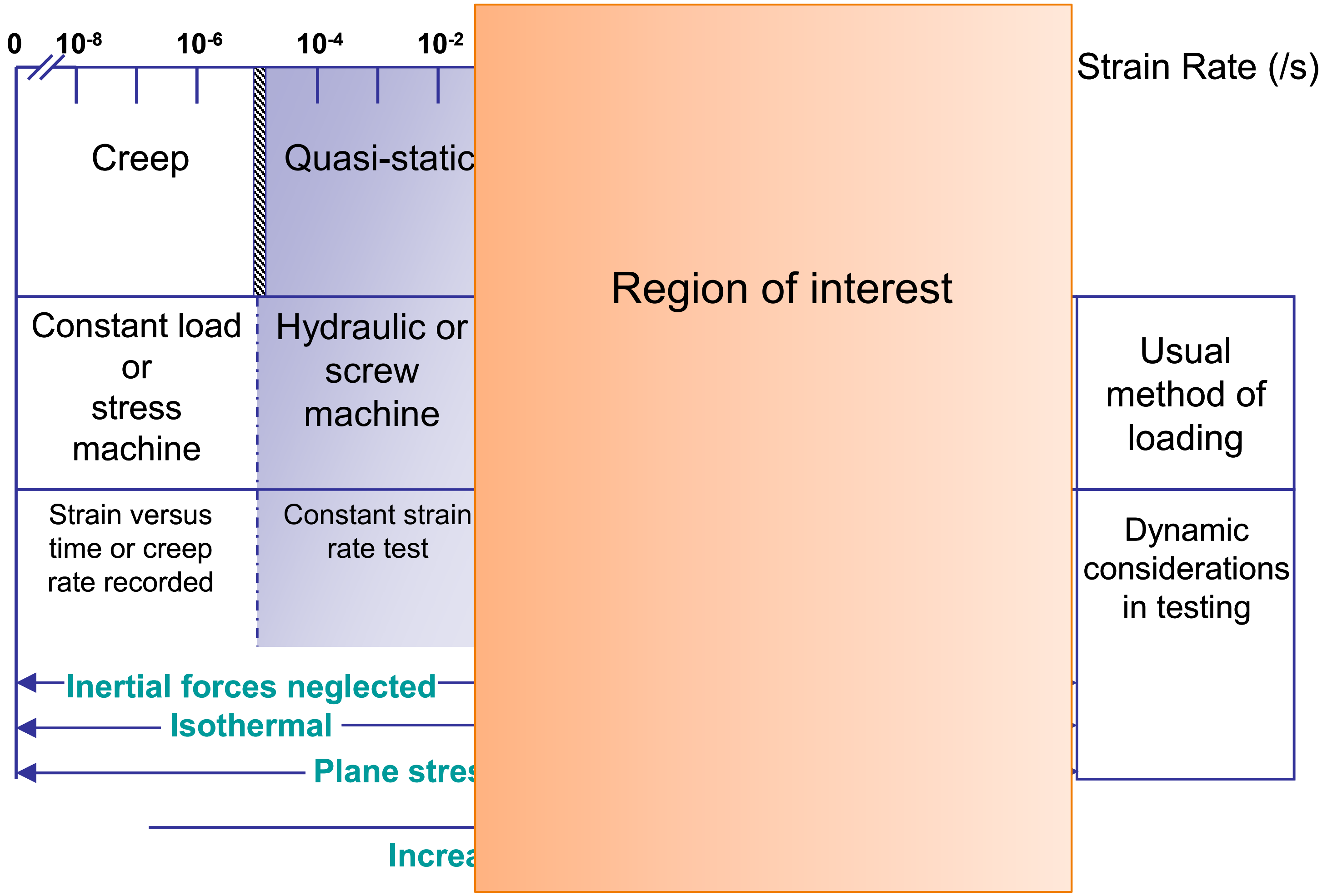


$$t_{12}(\omega) = \frac{\sigma_1(\omega)}{\sigma_2(\omega)}$$

$$\tau_{12} = \frac{\text{transmitted vibrational power}}{\text{incident vibrational power}} \propto {t_{12}}^2$$

- **Design goals/objectives:**
  - Spectral energy isolation (transmission rejection ratio)
  - Minimum complexity (N_{layers}, L_{system})
- **Constraints:**
  - Discrete material set (non-continuous property variables)
  - Defined layer pattern
  - Constant layer sizing (L_A, L_B)
- **Initial guess:**
  - Polysulfide/steel stack
- **Method:**
  - Discrete genetic algorithm w/local gradient-based improvement

Experimentation

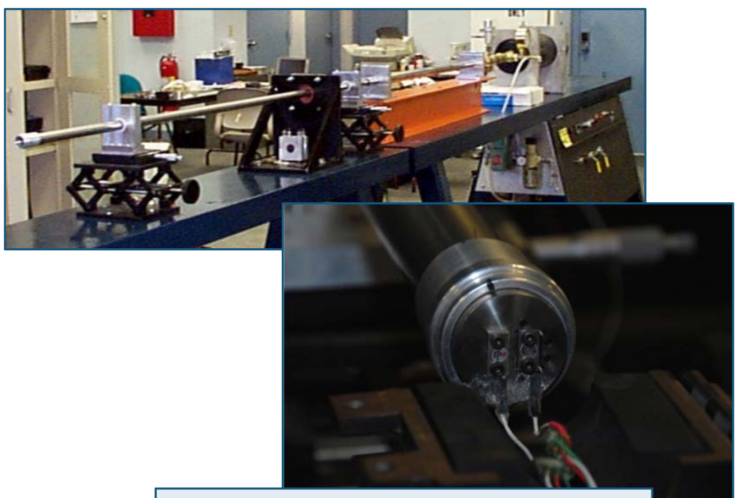


Nemat-Nasser, S. "High Strain Rate Tension and Compression Tests," *ASM Handbook Vol 8: Mechanical Testing and Evaluation, Materials Park:* ASM International, p. 429 (2000).

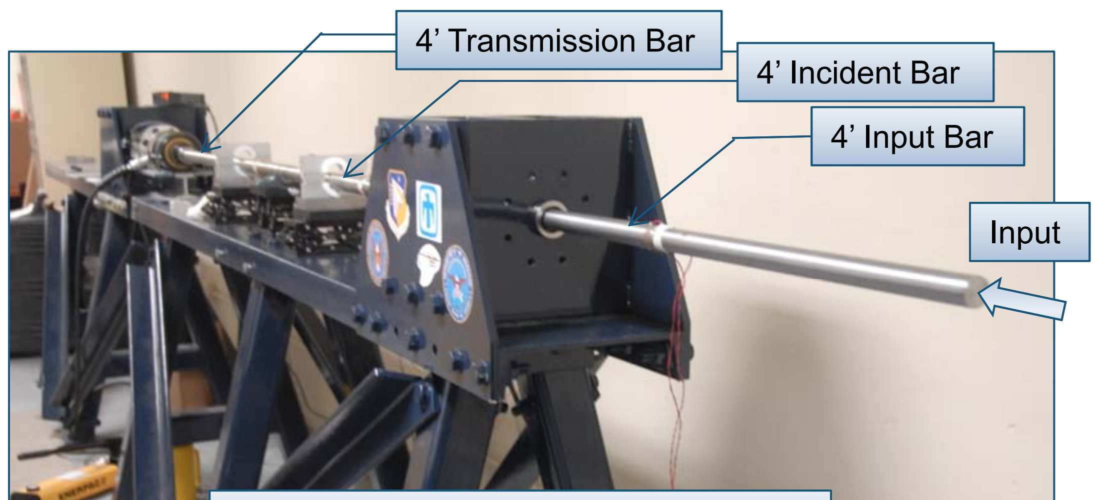
Experimentation

- **Hopkinson/Kolsky Bar**
  - Approximate uniaxial behavior
    - **Ideal SHPB-like case**
  - Simple Analysis
  - SOTA instrumentation

- **Preload Interface Bar**
  - Unique capability
  - Dynamic impulse with static quasi-unixial confinement
    - **Design to 50,000 lbf**



Hopkinson Bar @ AFRL



Preload Interface Bar @ AFRL

Way Ahead

- **Get started!**
  - Initial focus on optimization problem definition and figures of merit, theoretical framework, and “art of the possible”
- **Coordinate w/relevant efforts AFOSR tasks…**
  - Interested? Let’s chat!

  Examples:
  - Spectral Element Modeling (SEM)
    - **Nonlinear SEM, PI: Andrew Dick (Rice)**
    - **Wavelet SEM in Plates, PI: Ratan Jha (Clarkson)**
  - Soliton-Based Artificial Nervous System
    - **PI’s: “JK” Yang (USC), Amanda Schrand (AFRL)…**

Bio-inspired Artificial Nervous System Using Soliton-supporting Granular Phononic Crystals

Jinkyu “JK” Yang, Ph.D., Assistant Professor in Mechanical Engineering, University of South Carolina
Amanda Schrand, Ph.D., Materials Research Engineer, Air Force Research Laboratory, Munitions Directorate (AFRL/RWME)

DESCRIPTION & IMPACT

Solitons, self-reinforcing nonlinear wave pulses, are integral parts of biomembranes and nerves for the efficient transmission of electrochemical signals. Inspired by complex organ systems such as skin [Fig1A], we propose a novel artificial nervous system (ANS) composed of granular phononic crystals (GPCs) [Fig1B], which support highly nonlinear solitons. Analogous to the mechanism of neurons embedded within skin, the ANS will be designed to discern vibrations, temperature, impacts and other aspects of the environment. The anticipated impact: ***Micro-scale*** touch-sensitive transduction components (e.g., *tactile sensors)* and ***Macro-scale*** self-sensing mechanoreceptive structures that monitor and mitigate impact to the host structure in real time.

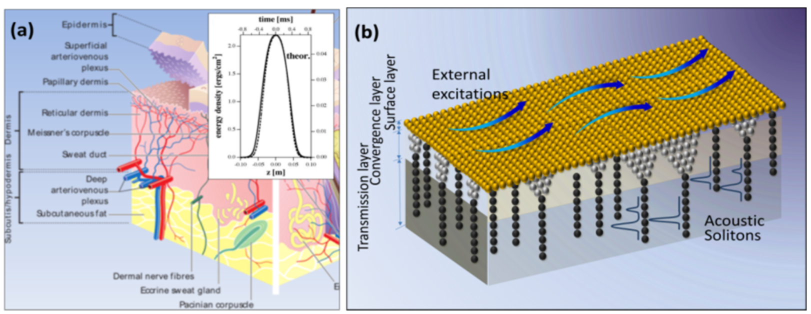


Fig. 1. Schematic depictions of (a) Mammalian skin displaying dermal nerve fibers and associated sensory mechanoreceptors such as Pacinian corpuscles (Inset: soliton packet). (b) Soliton-supporting ANS based on bio-inspired layering of granular phononic crystals.

APPROACH & OBJECTIVES

The ANS will be composed of multi-layered composite granular networks that convert surface stimuli into groups of compact-supported solitons in the underlying layer [Fig2A]. By analyzing the solitons transmitted by the granular chain networks, magnitudes and locations of external excitations will be identified. The main objectives are to: 1) Examine the *fundamental nonlinear wave dynamics* of granular phononic crystals and 2) Construct *proof-of-concept prototypes* [Fig2B] and experimentally verify external conditions and material properties (e.g., impact location and amplitudes).

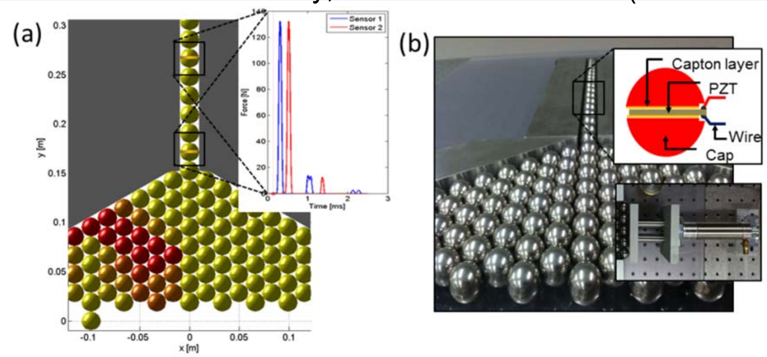
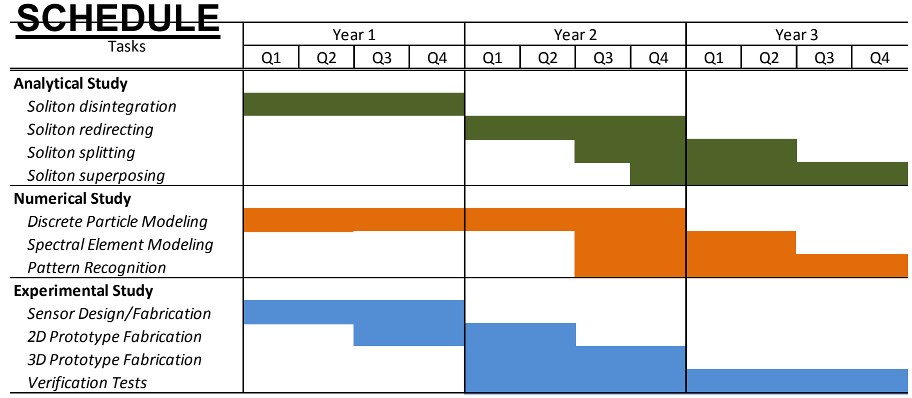


Fig. 2. 2D Granular phononic crystals configured in: (a) An elastic medium for detecting external impacts. (b) the experimental design and setup with a pneumatic actuator.

DELIVERABLES

Software: Discrete element model (DEM) for granular particle dynamics
Spectral element model (SEM) for interfacial wave propagation
Hardware: Soliton-supporting 2D/3D architecture of granular crystals

SCHEDULE



References

- **A. Schrand.** Direct current regulates process formation in human dermal fibroblasts in a collagen matrix . *Masters Thesis*, Department of Biological Sciences, Wright State University, Dayton, OH, 2001.
- **J. Yang**, *et al.* Interaction of highly nonlinear solitary waves with elastic linear media, *Physical Review E*, 83: 046606, 2011.
- N. Boechler, **J. Yang**, *et al.*, Tunable vibration band gaps in one-dimensional diatomic granular crystals with three-particle unit cells, *Journal of Applied Physics*, 109: 074906, 2011.
- **J. Yang**, *et al.*, Amplitude-dependent attenuation of compressive waves in curved granular crystals constrained by elastic guides, *Acta Mechanica,* 223(3): 549–562, 2012.

AFOSR-BAA: Multi-Scale Structural Mechanics and Prognosis (Program manager: Dr. Les Lee)

Summary

- **Impact and penetration loads are extremely harsh thermomechanical environments**
  – Broadband & stochastic environment, nonlinear, etc.
- **Several methods have been proposed to mitigate this environment (i.e., shock isolation)**
  – TBD
- **Our research effort proposes harnessing metamaterials framework with extension…**
  – Extended multilayer spectral analytic method
  – Topological multiobjective optimization with uncertainty
  – Validation using high rate experiments
- **Open and willing to collaborate on research…**

Questions?

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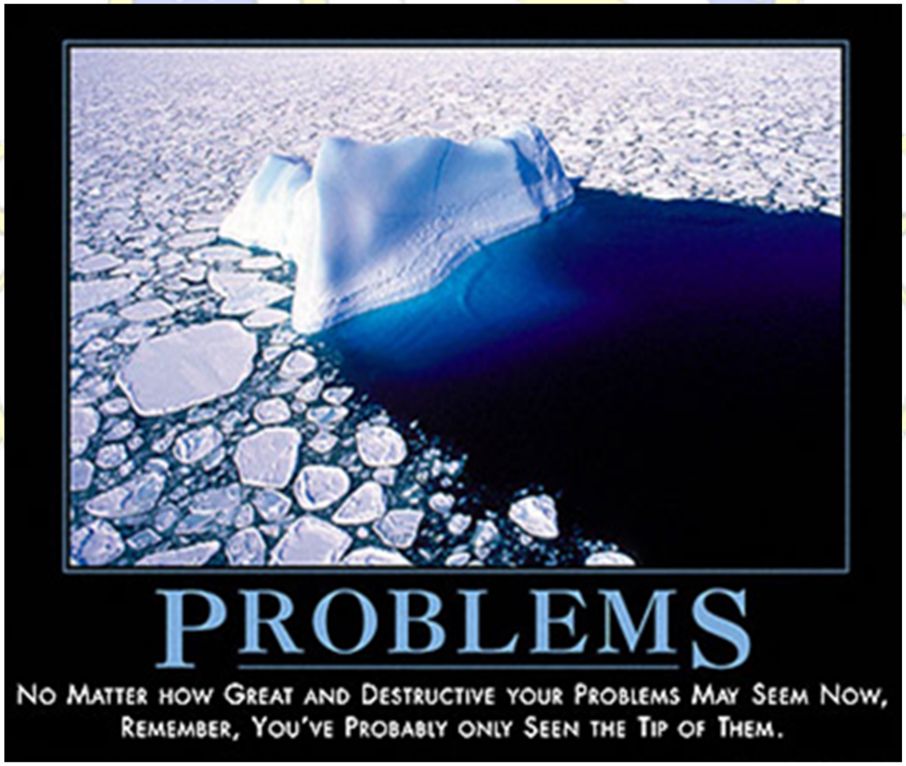


www.despair.com

Backup Slides

References

[1] Shelby, R. A., Smith D.R., Shultz S., and Nemat-Nasser S.C., 2001, "Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial", *Applied Physics Letters* 78 (4), pp. 489-491.

[2] Lu, M.-H., Feng, L., and Chen, Y.-F., 2009, "Phononic crystals and acoustic metamaterials," Materials Today, 12(12), pp. 34-42.

[3] Yang, S., Page, J. H., Liu, Z., Cowan, M. L., Chan, C. T., and Sheng, P., 2004, "Focusing of Sound in a 3D Phononic Crystal," Physical Review Letters, 93(2), 024301.

[4] Vasseur, J. O., Deymier, P. A., Khelif, A., Lambin, P., Djafari-Rouhani, B., Akjouj, A., Dobrzynski, L., Fettouhi, N., and Zemmouri, J., 2002, "Phononic crystal with low filling fraction and absolute acoustic band gap in the audible frequency range: A theoretical and experimental study," Physical Review E, 65(5), p. 056608.

References

[5] Liu et al., 2000, “Locally Resonant Sonic Materials,” *Science* 289 (5485), pp 1734-1736.

[6] Tanaka, Y., and Tamura, S.-I., 1999, “Two-dimensional phononic crystals: surface acoustic waves,” *Physica B: Condensed Matter* 263-264, pp. 77-80.

[7] Pennec, Y., Djafari-Rouhani, B., Vasseur, J. O., Khelif, A., and Deymier, P. A., 2004, "Tunable filtering and demultiplexing in phononic crystals with hollow cylinders," Physical Review E, 69(4), p. 046608.

[8] Hong, T., Chunrong, L., and Xiaopeng, Z., 2004, "Tunable characteristics of a flexible thin electrorheological layer for low frequency acoustic waves," Journal of Physics D: Applied Physics, 37(16), p. 2331.

[9] Dhar, L., and Rogers, J. A., 2000, "High frequency one-dimensional phononic crystal characterized with a picosecond transient grating photoacoustic technique," Applied Physics Letters, 77(9), pp. 1402-1404.

Shock-Mitigating Multilayered Mechanical MetaMaterials (SM^5)

LRIR Synopsis:
1. Fuzes CTC
2. Multifunc. Materials
3. PM: Dr. Les Lee
4. J. Foley/B. Martin

Technology Objective

- Discover/develop/demo methods for attenuating the severe mechanical environment in penetration:
  - High amplitude stresses/forces
  - High frequency content (broadband) waves
  - Multiaxial loading profiles
  - Stochastic environment
- Proposed investigation uses mechanical metamaterials
  - Acoustic metamaterials have been demonstrated to have physically impossible transport properties: negative density, wave reversal/focusing, band mod
  - Conceptual foundations in superlattices, phononic crystals for wave interactions, effective properties

Schedule/Cost (JON)

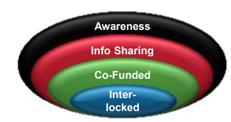
	FY12	FY13	FY14	FY15	FY16
Program Initiation					
1-D Mitigating MM					
2-D/3-D Mitigating MM					
Program completion					
Civ.Salary ($K)	**0.0**	**125**	**100**	**100**	
ARA (Onsite) Salary		**75**	**80**	**90**	
Travel		**10**	**10**	**10**	
Equipment, T&E		**40**	**60**	**50**	
Total ($K)		**250**	**250**	**250**	

Tech Challenges/Approach

- Challenge: Shock mitigation schemes are typically one-shot (i.e., use deformation); no description of dissipation
  - S&T Approach: "Bottom up": Develop 1-D analytic framework and solve wave eqns
  - Define, predict, & validate spectral coefficients, constitutive response, effective transport props
  - Define dissipation mechanisms and wave properties vs. structure, material, length scales
- Challenge: Several candidate material classes
  - S&T Approach: Simulate mitigation; calculate effective properties; use topological optimization
- Challenge: Real environments induce nonlinearities
  - S&T Approach: Add in frequency, structure nonlinear terms

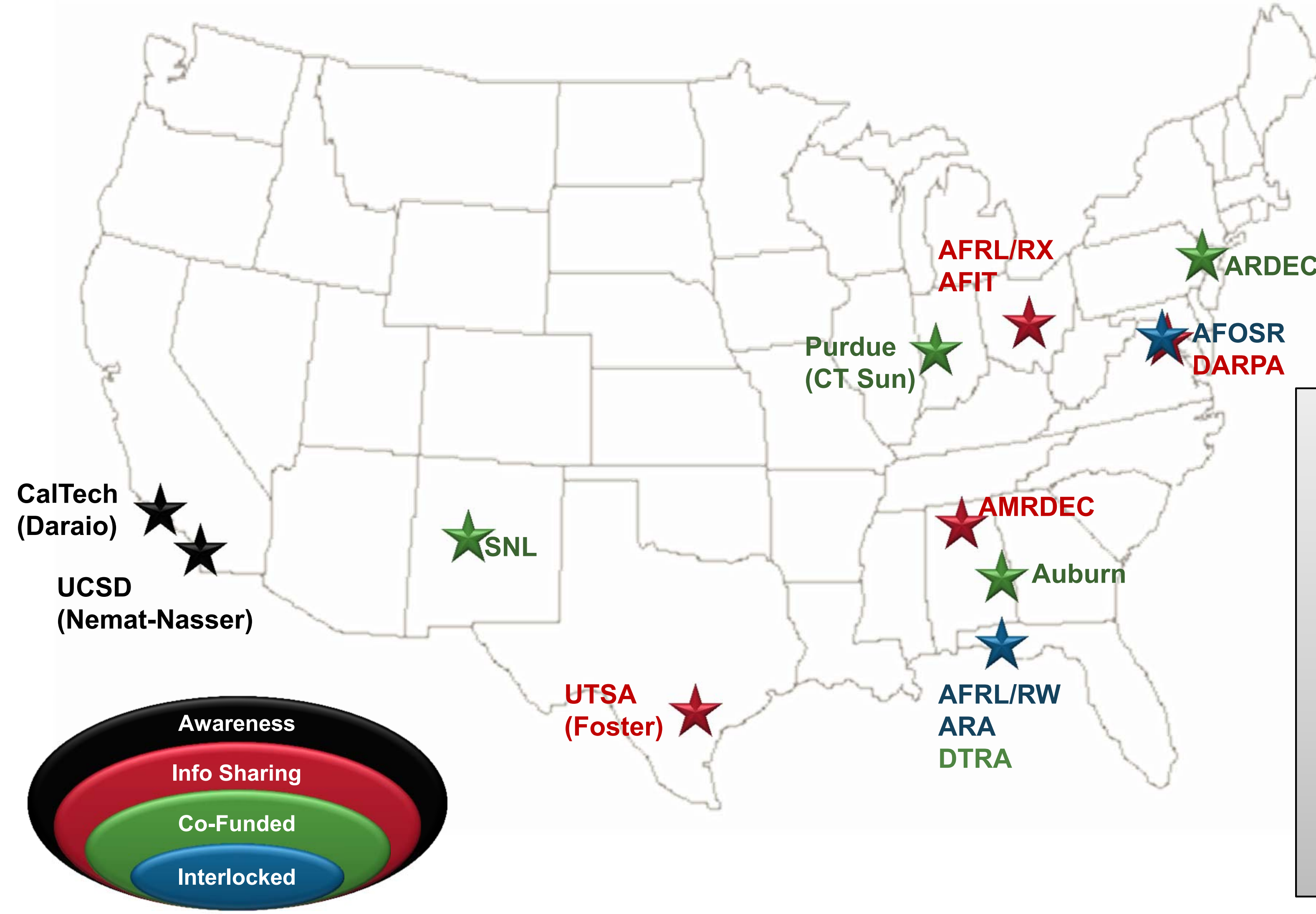
Mission Alignment & Benefits; Partnerships

- **RW Strategic Alignment:**
  - Co-developed by hard target fuzing, warhead sub-CTC's
  - Supports S&T Vector 3, "Hold high value targets at risk"
  - Mitigation schemes are broadly applicable to penetrating warhead subsystems and critical fuze components: sensors, firesets, processors, batteries, etc.
  - Also enables directional inertial coupling for future "Brilliant Fuzing" concepts



- **Industry/University/DoD Partners:**
  - Leverage AFRL/RX, RY for fabrication
  - C.T. Sun (Purdue) and X. Zhang (Boston U.) via AFOSR
  - O. Mondain-Monval, A. Aradian (CNRS, France) via EOARD

Collaborations and Interactions



International

University of Oxford (UK)